



Performance prediction of micro-CHP systems using simple virtual operating cycles



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HIGHLIGHTS

- A methodology to estimate in advance actual performance of micro-CHP systems is given.
- A Virtual Operating Cycle is introduced for the micro-CHP system.
- Limited information on the micro-CHP from manufacturer is used.
- Procedure can be used for fast estimation of energy and environmental performance.
- Application to residential user is described.

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ABSTRACT

This paper presents a general methodology to roughly estimate in advance the actual performance of μ -CHP (micro Combined Heat and Power) systems in one year of operation, by means of limited information on the CHP prime mover efficiency and emission factors in selected set points and by means of a simplified prediction model of the operating cycle. The carried out analysis has been applied to several market-available and under development μ -CHP units of different technologies (Internal Combustion Engines, Micro Gas Turbines, Organic Rankine Cycles, Stirling, Thermo Photo Voltaic, Fuel Cell), operated under a hypothetical virtual operating cycle. The virtual cycle is obtained in this paper on the basis of the year thermal demand of a domestic user, assuming thermal load following of the CHP system. The methodology can be generalized to different applications and different management logics of the CHP system.

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1. Introduction

Cogeneration, i.e., Combined Heat and Power (CHP) generation, is a viable strategy often promoted [1] as one of the most promising available solutions for energy saving and emission reduction [2]. Micro-CHP systems, i.e. generators with nameplate electric power output roughly below 100 kW and more often in the range 1–10 kW, are under investigation in many industrialized and developing countries, mostly as potential substitute of domestic boilers or in isolated applications.

The issue of μ -CHP performance assessment is of great importance (examples of performance characterization can be found in Refs. [3,4]), especially considering new machines based on not-fully-developed or less consolidated technologies and with regard to the local regulations, as highlighted by Peacock et al. in Ref. [5].

The available/under development technologies in this sector (review of the current technology can be found in Refs. [6,7] and in Ref. [8] analyzing Energy, Economic and Environmental implications) are small Internal Combustion Engines (ICE), Micro Gas Turbines (MGT), Micro Rankine Cycles (MRC), Stirling Engines (SE) Fuel Cells (FC) systems and Thermo Photo Voltaic (TPV) generators; these systems do not have an equal level of technological development or maturity (see Refs. [9,10] for FC μ -CHP performance data and [11] for TPV prototype application). A large market potential for Micro-CHP has been identified since more than ten years ago, as highlighted for example by Dentice d'Accadia et al. in Refs. [12], but local, regional and international regulations on CHP requiring a detailed experimental monitoring of CHP systems (e.g. the national Italian and European rules on “high-efficiency” CHP require to fulfill some prescriptions, which inevitably lead to measurements on the thermal & electric production) can be a barrier to the diffusion in small scale applications.

The measurement of CHP systems actual performance and the consequent merit qualification, highlighted for example by

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Verbruggen in Ref. [13], is more complicated in case of μ -CHP systems, where on-site performance monitoring and acquisition systems are not easily installable in a cost-effective way.

In such a scenario, a viable strategy to pursue could be to approximate in advance the actual operation with virtual simple operating cycles, in order to predict the realistic energy/environmental and also economic performance of a μ -CHP system defining a standardized, simplified, fast and cost effective procedure.

2. Micro-CHP nameplate and part-load performance data trends

Micro-CHP performance data are usually provided by manufacturers taking as reference base load operation; for example Fig. 1 reports data of electric efficiency thermal efficiency and NOx emissions collected by the authors in previous studies [2,14], referring to various commercial CHP and μ -CHP systems. Depending on the system technology and electric size, the nameplate electric efficiency can range in between 10 and 30% and the thermal efficiency at maximum recovered thermal power is in between 40% and around 90%. Specific emissions at full power are significantly affected by the Micro-CHP technology (see Fig. 1 referring to NOx and CO) and for a given μ -CHP kind, they are roughly decreasing with electric efficiency.

Micro-CHP systems have natural potential suitability for different civil, tertiary and industrial applications (see few application studies in Refs. [5,15–23]), such as residential buildings, hospitals, supermarkets, sporting centers, etc., where a significant thermal and cooling demand is associated to the user electricity demand. In such various applications, it is common to observe time-varying electric and thermal energy demand. The actual energy/environment performance of the μ -CHP systems can be

significantly affected by the operating cycle, which is difficult to predict in details before the CHP system is installed.

Moreover, the economic convenience of CHP systems strongly depends on the specific application scenario in which the CHP system operates, as pointed out in previous studies of the authors [14,15] and others [21–25]. Nevertheless, very limited data on the forecasted operating sequence of the μ -CHP over the year can be available in many practical cases.

Significant variations in the CHP performance occur at part load conditions, in comparison with base load conditions, as shown in Fig. 2a and b reporting, as examples, normalized electric and thermal efficiency plots versus the normalized electric load, for three different CHP systems (namely Capstone C30 MGT is CHP1 in Fig. 2, Caterpillar G3306NA ICE is CHP3 and Turboc 100 MGT is CHP2 [26–28]). Moreover, also pollutant emissions are largely affected by part-load conditions, as provided in Fig. 2c and d, presenting NOx and CO specific emission trends per unit of output electric power, for four CHP systems, namely two ICEs (Cat G3306NA is CHP6, AVL is CHP4) and two MGTs (Elliot TA80 is CHP5, Garrett GTP-30-67 is CHP7), according to Refs. [26,29–31]. The electric efficiency plots are increasing with power and the thermal efficiency is decreasing, for all the considered prime mover; on the contrary, the gas emission data trend can be increasing or decreasing versus load depending on the specific prime mover model. The shown performance quantities are strongly dependent on the load, with changes in NOx and CO of various orders of magnitude moving from full load to minimum load.

Thus, the limited but representative number of provided trends, concerning energy/environmental performance of selected μ -CHP systems, is clearly indicating the need to take into account the actual load occurrence in specific applications, including definitely part loads, in order to correctly predict the overall yearly primary energy consumption and pollutants production.

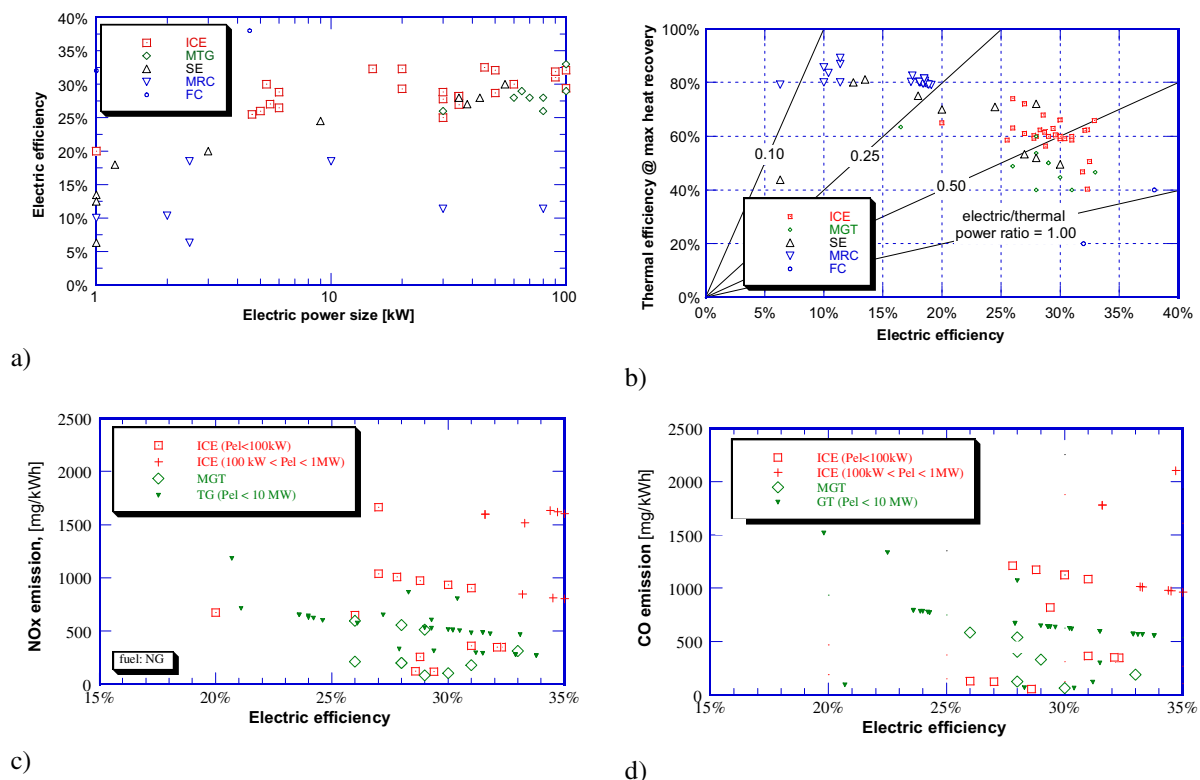


Fig. 1. Base load micro-CHP nominal performance data: a) electric efficiency vs size; b) thermal efficiency vs electric efficiency; c) NOx and d) CO emissions, for selected CHP systems.

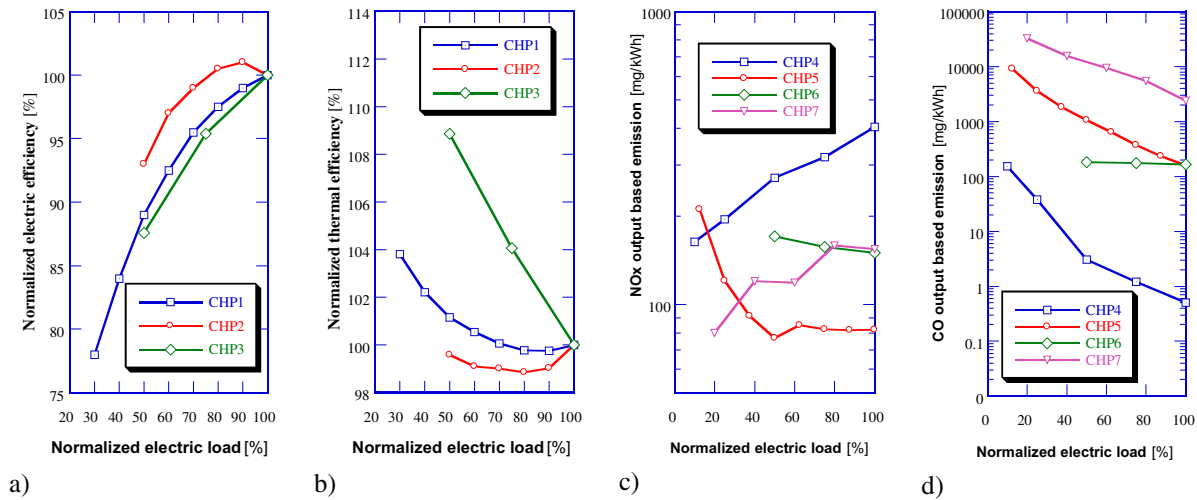


Fig. 2. Part-load performance of selected μ -CHP systems: a) electric efficiency; b) thermal efficiency; c) NOx emissions; d) CO emissions.

3. Load profile for micro-CHP applications: residential case

Micro-CHP systems are investigated here taking into account a typical application scenario in a residential building. The thermal energy demand and the electricity demand have been estimated in this study according to Refs. [32–34] with reference to a typical Italian household utility; the daily normalized thermal demand is reported in Fig. 3; the monthly scaling factor for heating demand, obtained considering the statistical data of mean ambient temperature in several Italian cities (located in national climatic zones D and E, with variable number of heating degree hours between 1500 and 2700 [14]), is in Fig. 4 and the daily request for hot water is also given in Fig. 3. A statistical approach [32–34] has been used to calculate the electric energy request, obtaining the daily profile shown in Fig. 5a and b, respectively for a typical winter and summer day.

In this study, the μ -CHP system is primarily considered operated in thermal load following; therefore, the key load curve used in the following of the paper is the thermal load curve. Nevertheless, the described methodology can be extended also to μ -CHP systems working in electric load following operating mode. In this last case the reference load curve is the electric load.

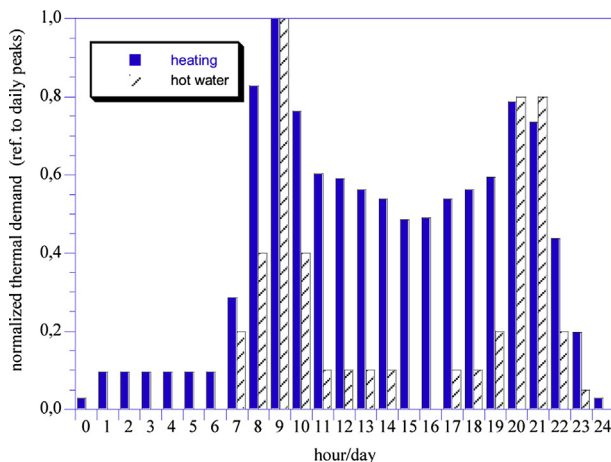


Fig. 3. Daily normalized thermal energy demand [14].

In this study, starting from the daily thermal energy demand profile and the month scaling factors the monotonic year load curve has been obtained, as shown in Fig. 6.

4. Methodology to define micro-CHP virtual operating cycles

The proposed methodology to obtain a simplified virtual operating cycle of a μ -CHP system is based on the monotonic load curve. Fig. 7 shows a block diagram describing the steps of the followed methodology (which have been implemented in an Excel-VBA calculation worksheet): the preliminary first two steps, namely #1 the collection of input detailed thermal load data of the user and #2 the calculation of the yearly thermal demand, required to obtain the real monotonic curve (e.g. Fig. 6), have been described for example in a previous study of the authors [14]; this preliminary detailed calculation can be substituted with a simplified procedure, resulting in the subsequent two steps, namely #3 the calculation of a simplified monotonic curve by means of an empirical model and #4 the calculation of the simple virtual operating cycle, both described in the following part of the paper.

It should be pointed out that the method is “general purpose” for different applications, even if it is here shown for a case of single domestic user. The actual curve (normalized in Fig. 6 with respect to the demand peak value) has been calculated considering a

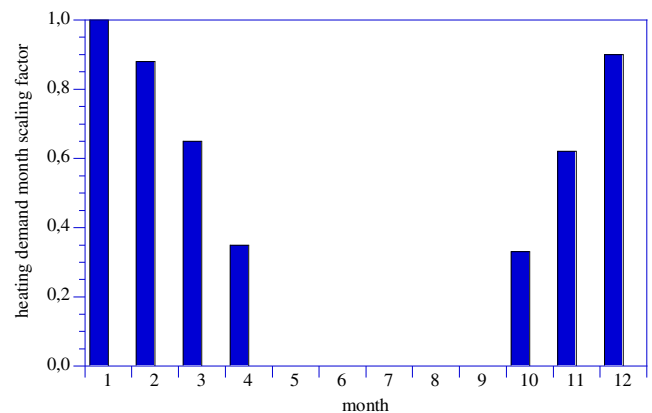


Fig. 4. Month scaling factor of heating energy demand [14].

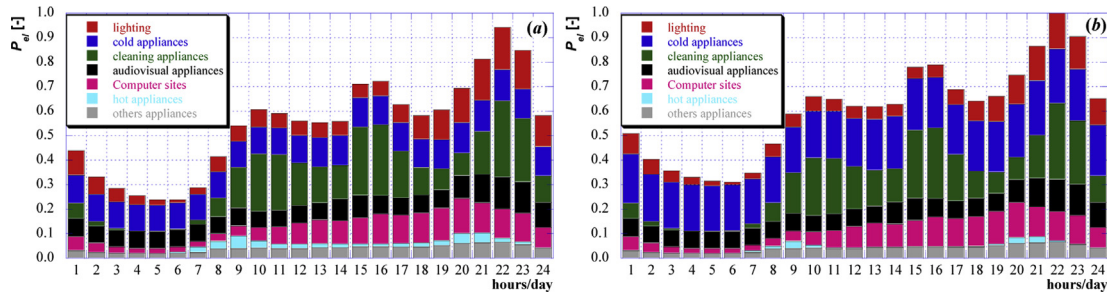


Fig. 5. Dimensionless electrical load curve in a winter day (a) and in a summer day (b) [32].

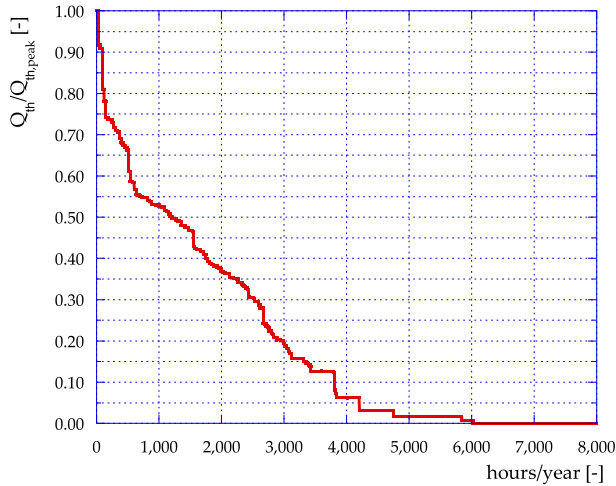


Fig. 6. Monotonic thermal demand curve for residential application, normalized with peak.

specific residential user in north of Italy, requiring 20 MWh/year of thermal energy; the same user is supposed to consume 3 MWh/year of electricity.

The monotonic curve of the real thermal demand of the considered domestic single user, indicated here as $R(t)$, is presented

in Fig. 8 (continuous line); it can be observed that this trend shows a peak value (indicated as $Q_{th,peak}$) equal to about 12.6 kW (obtained considering the hourly based demand) and a total number of hours of thermal demand equal to about 6000.

4.1. Empirical model of the monotonic demand curve

A simplified empirical monotonic curve $S(t)$ is introduced in this study to model the actual demand $R(t)$ (step #3 of Fig. 7); this simplified curve, which approximates the real monotonic curve, is based on a simple analytical modeling expression, introduced in order to interpolate two characteristic points (C1 and C2 in Fig. 8) whose coordinates on the plane hours-required heat are as follows:

$$C1 : (h_1; Q_{th,1}) \quad (1)$$

$$C2 : (h_2; Q_{th,2}) \quad (2)$$

where:

$$Q_{th,1} = f_1 \cdot Q_{th,peak} \quad (3)$$

$$Q_{th,2} = f_2 \cdot Q_{th,peak} \quad (4)$$

while f_1 and f_2 are two dimensionless multipliers of the peak thermal power ($h_2; Q_{th,peak}$).

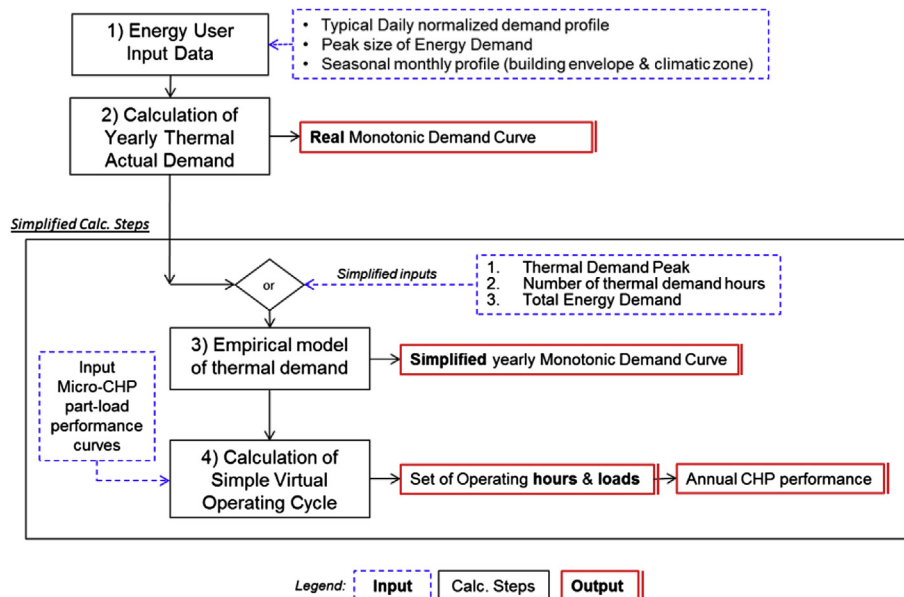


Fig. 7. Block diagram of the methodology.

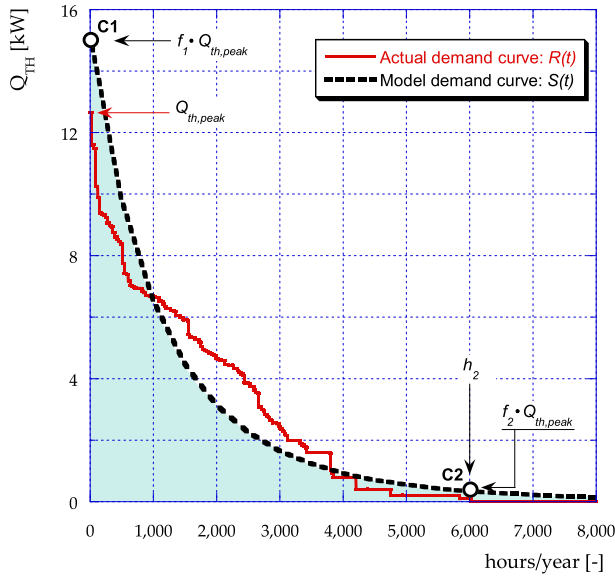


Fig. 8. Actual and modeled monotonic thermal demand curves for a residential user.

For the case in study, the following data are considered: $h_1 = 0$, $f_1 = 1.2$ and h_2 equal to the maximum number of hours of thermal demand (6000 h in the assumed case, see Fig. 8), found in order to match the actual demand in this and similar cases.

The last term f_2 can be calculated equating the annual energy corresponding to the actual demand curve with the annual energy given by the model, i.e. the following identity should be satisfied:

$$\int_0^{8760} R(t) \cdot dt = \int_0^{8760} S(t) \cdot dt \quad (5)$$

The introduced analytical expression of the modeled monotonic curve $S(t)$ is:

$$S(t) = f_1 \cdot Q_{th,peak} \cdot \frac{K}{[(h_2 - h_1) + t]^n} = f_1 \cdot Q_{th,peak} \cdot \frac{K}{(h_2 + t)^n} \quad (6)$$

where:

$$K = h_2^n \quad (7)$$

$$n = \frac{\ln(f_2/f_1)}{\ln\left(\frac{h_2}{2h_2-h_1}\right)} = \frac{\ln(f_2/f_1)}{\ln(0.5)} \quad (8)$$

Thus, the model curve $S(t)$ (dotted line in Fig. 8) can be used to estimate the thermal demand of a domestic user, when no other information except the peak thermal demand ($Q_{th,peak}$), the hours of request (h_2) and the total required energy are known, as shown in Fig. 7. The introduced model was derived by testing and comparing different mathematical functions; the proposed one was found to fit better the shape of the empirical data, by quickly adjusting the few empirical coefficients.

4.2. Micro-CHP virtual operating cycle

In order to obtain a simplified operating cycle of a μ -CHP system, the monotonic demand model $S(t)$ and the part-load curve of the μ -CHP are used (step #4 of Fig. 7), according to the procedure described below and based on the graphs of Fig. 9. In particular, Fig. 9(a) shows the part-load performance curves of a μ -CHP system

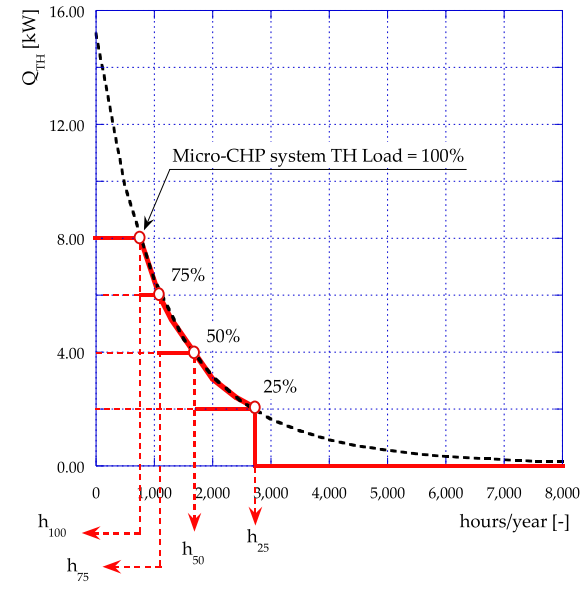
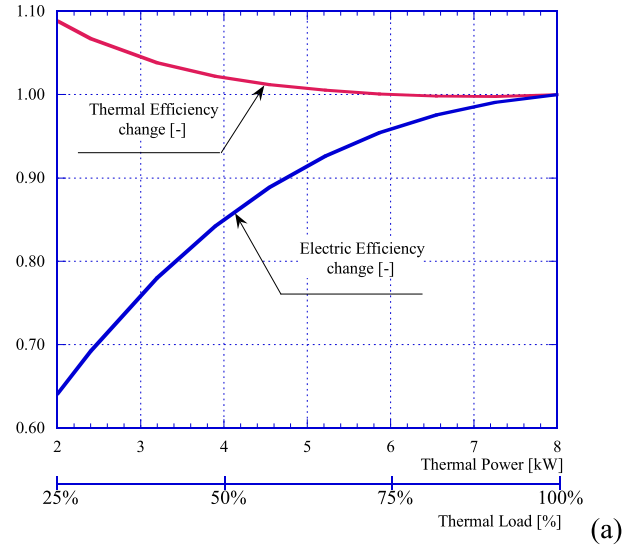


Fig. 9. Micro-CHP part-load performance curves (a) and significant operating points (b).

in terms of electric and thermal efficiency change versus thermal output load. Fig. 9(b) shows the model monotonic demand curve (dotted black line), and the assumed μ -CHP system virtual cycle (red line and highlighted points).

More in details, according to the considered model, only significant output load set points of the μ -CHP are taken into account, e.g., 100%, 75%, 50% and 25% of the design thermal power, in case of Fig. 9. The considered thermal size of the μ -CHP system is lower than the demand peak (as shown in Fig. 9(b)) and, according to the assumed μ -CHP load curve, in some periods of the years a deficit of produced thermal power occurs, in comparison with the demand; moreover, a minimum power output value of the μ -CHP system (25% in Fig. 9(b)) is also considered. Thus, an external additional source (e.g., an auxiliary boiler) is considered, in order to fulfill the residual demand of power. Using Fig. 9(b), it is possible to obtain the number of operating hours of the μ -CHP systems corresponding to a given load. For example, the selected μ -CHP system operates for h_{50} h at 50% of the peak load. Three different virtual cycles,

corresponding to different values of the μ -CHP nominal thermal power output, are shown in Fig. 10. As the nominal thermal size $Q_{th,DES}$ of the prime mover decreases (i.e., $Q_{th,DES}/Q_{th,peak}$ decreases), the required energy integration with auxiliary systems (boiler or thermal storage) increases. Table 1 provides the values of the number of operating hours at the different considered significant μ -CHP output loads, for various sizes of the μ -CHP system, in terms of full thermal load with reference to the demand peak. Each series of data describes a simplified virtual operating cycle of the micro-CHP system. These values are calculated on the basis of the modeled monotonic demand curve of Fig. 8. In case of different applications, the corresponding operating hours would change, obtaining different simplified virtual operating cycles for the μ -CHP system.

4.3. Micro-CHP system annual average efficiency

On the basis of the introduced model for the user demand given by the function $S(t)$ and on the basis of the assumed virtual cycle of Fig. 9(b), the annual average thermal efficiency ($\eta_{th,S}$) and average electrical efficiency ($\eta_{el,S}$) can be estimated. These mean efficiency values are calculated as weighted average values of part-load efficiency, obtained from Fig. 9(a) considering different thermal loads; the used weights are the interval of hours for each load step:

$$\eta_{th,S} = \left[\eta_{th,100} \cdot h_{100} + \frac{\eta_{th,75} + \eta_{th,100}}{2} \cdot h_{75} + \frac{\eta_{th,50} + \eta_{th,75}}{2} \cdot h_{50} + \frac{\eta_{th,25} + \eta_{th,50}}{2} \cdot h_{25} \right] / h_{TOT} \quad (9)$$

$$\eta_{el,S} = \left[\eta_{el,100} \cdot h_{100} + \frac{\eta_{el,75} + \eta_{el,100}}{2} \cdot h_{75} + \frac{\eta_{el,50} + \eta_{el,75}}{2} \cdot h_{50} + \frac{\eta_{el,25} + \eta_{el,50}}{2} \cdot h_{25} \right] / h_{TOT} \quad (10)$$

where the $\eta_{th,i}$ and $\eta_{el,i}$ values are the thermal and electric efficiency at the i -th load set point value of the micro-CHP system. The $\eta_{th,S}$ and $\eta_{el,S}$ values can be used to calculate the annual performance indexes of the micro-CHP system; for example the Primary Energy Saving (PES) index, used to qualify the CHP performance in Europe, can be obtained according to Ref. [1].

As it is evident from the equations given above, the model takes into account the fact that the micro-CHP system is actually operated in thermal load following along the monotonic demand curve;

Table 1

Virtual Cycle or operating hours of a μ -CHP at different output loads, for various sizes of the micro-CHP system, in case of residential application.

$Q_{th,DES}/Q_{th,peak}$ [–]	Load [%]			
	100	75	50	25
	Hours of the virtual cycle			
	h_{100}	h_{75}	h_{50}	h_{25}
1.00	203	334	503	951
0.90	323	341	513	969
0.80	461	348	524	990
0.70	620	358	536	1015
0.60	810	367	552	1044
0.50	1040	380	571	1079
0.40	1333	396	594	1124
0.30	1729	417	627	1183
0.20	2323	449	675	1276
0.10	3447	510	766	1442

Table 2

Tested micro-CHP systems.

Micro CHP	Type	P_{el}	η_{el} [%]	η_{th} [%]	P_{el}/Q_{th}
1 Genlec™ Kingston	MRC	1.00	10	80	0.13
2 Otag LION™	MRC	2.00	10	84	0.12
3 MTT™	MGT	2.50	17	64	0.26
4 Infinia micro CHP	STL	1.00	13	80	0.16
5 Sunmachine™	STL	3.00	20	70	0.29
6 Honda Ecowill™	ICE	1.00	20	65	0.31
7 Senertec Dachs™	ICE	5.00	26	63	0.41
8 Senertec Dachs™ cd.	ICE	5.00	26	74	0.35
9 SOFC HoTbox™	FC	0.45	33	20	1.65

in order to account for this fact, in each interval i -th of hours in which the micro-CHP output load is constant, the corresponding i -th thermal efficiency value is equal to the mean between $\eta_{th,i}$ and $\eta_{th,i+1}$, and analogously for the electric efficiency.

In order to verify the above described modeling approach for calculation of the annual average performance with a simplified virtual cycle based on few discrete operating points, this simplified procedure has been compared with a more detailed calculation approach, in which the actual part load conditions are considered. The average thermal and electrical efficiency values have been calculated in details by using the actual monotonic demand curve $R(t)$ and considering detailed part-load efficiency values of the micro-CHP system and not only a discrete number of set-points.

Different market-available or under development micro-CHP systems of various technologies have been taken into account

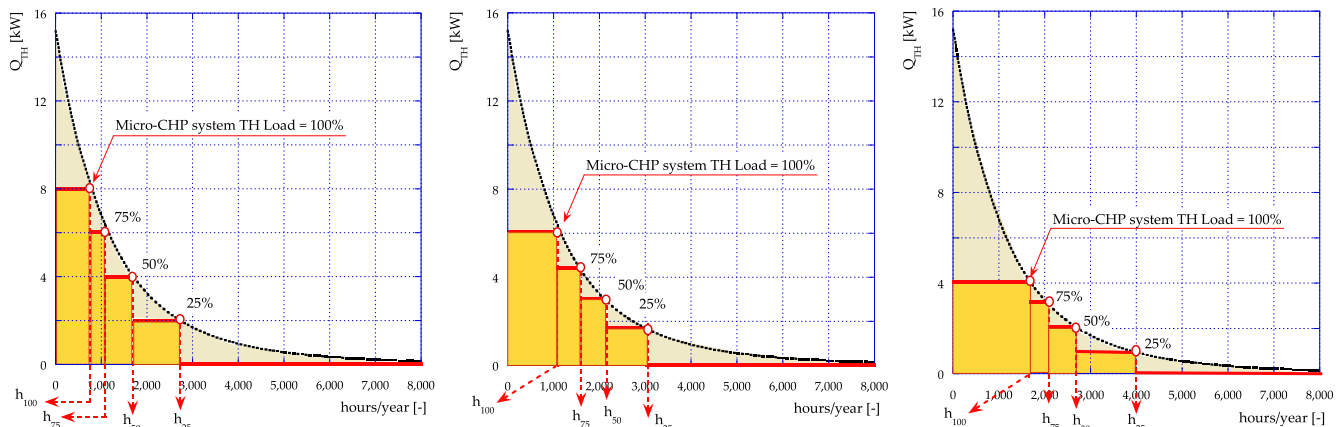


Fig. 10. Example of virtual cycles for three different thermal sizes of the Micro-CHP system.

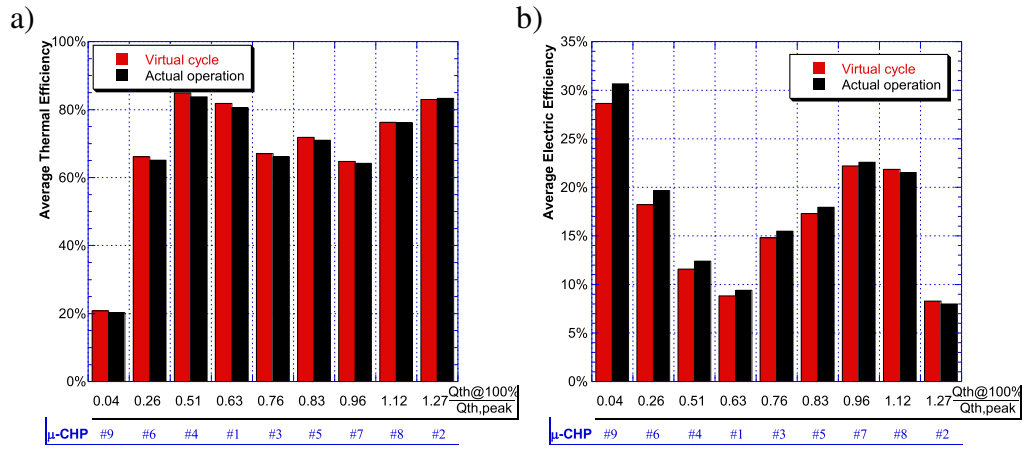


Fig. 11. a) average thermal efficiency; b) average electric efficiency.

(source papers for input data are [9,14,35]), as summarized in Table 2, which collects power size and full load efficiency values. For each one of the μ -CHP system, the part load efficiency behavior has been modeled according to the normalized plot of Fig. 9(a).

The obtained results of a comparison between the two calculation approaches are shown in Figs. 11 and 12 for all the examined μ -CHP systems, sorted for increasing thermal power size. Fig. 11(a) provides the average thermal efficiency and Fig. 11(b) the average electric efficiency over a year of operation. Fig. 12(a) shows the corresponding electric-to-thermal energy production and finally Fig. 12(b) provides the resulting value of the Primary Energy Saving (PES) index evaluated according to the European regulation [1] regarding CHP systems.

The calculations show a good matching between the average values obtained with the two procedures (maximum differences are of the order of 2 percentage points for the electric efficiency and less than 1 percentage point for the thermal efficiency), demonstrating the viability of the introduced simplified operating cycle for various μ -CHP systems. The Calculated PES values are positive in all cases, obtaining significant savings, while thermal production is predominant in most of the cases, with limited electric production (the only incentivized contribution in many countries).

Finally, an estimation of annual average NOx and CO emission values has been carried out, by using the above described

methodology based on the virtual operating cycle and on the μ -CHP system emission factors at full and part-load conditions (in a selected, limited number of operating conditions). This last method is often used, but it is not correct, due to the part load operation and the frequent higher part-load emissions of many CHP systems, as also shown in Fig. 2. Results are reported in Fig. 13, only for the μ -CHP systems for which the emission factors can be found in literature or in different sources [35–38]. The specific emissions of each pollutant $\delta_{P,S}$ are calculated as weighted averages of the emission factors at full and part-load conditions $\delta_{P,i}$, according to the following equation:

$$\delta_{P,S} = \left[\delta_{P,100} \cdot h_{100} + \frac{\delta_{P,75} + \delta_{th,100}}{2} \cdot h_{75} + \frac{\delta_{P,50} + \delta_{P,75}}{2} \cdot h_{50} + \frac{\delta_{P,25} + \delta_{P,50}}{2} \cdot h_{25} \right] / h_{TOT} \quad (11)$$

Despite the limited available data, the shown values and the virtual cycle approach demonstrate the possibility to obtain more conservative information on the environmental performance, in comparison with an estimation based only on the nameplate full-load emission factors.

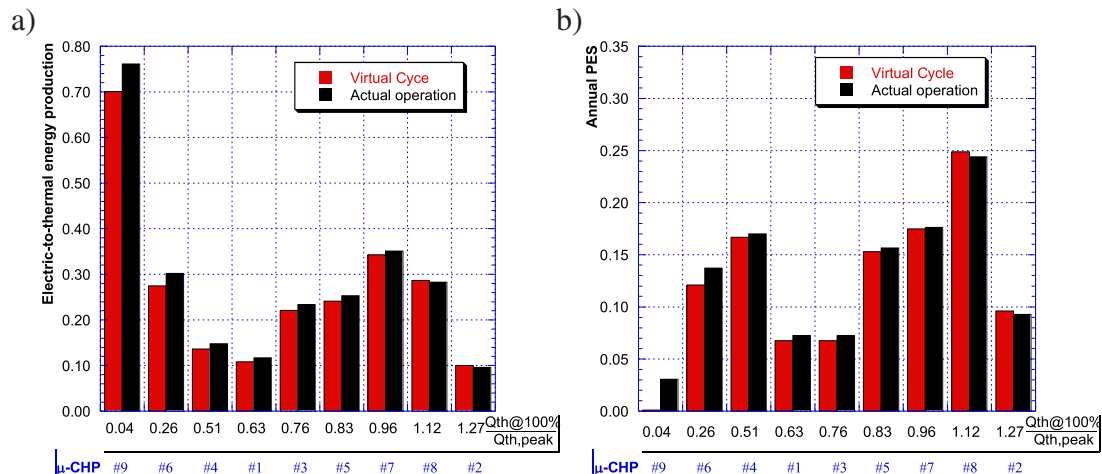


Fig. 12. a) electric-to-thermal energy production; b) Primary Energy Saving.

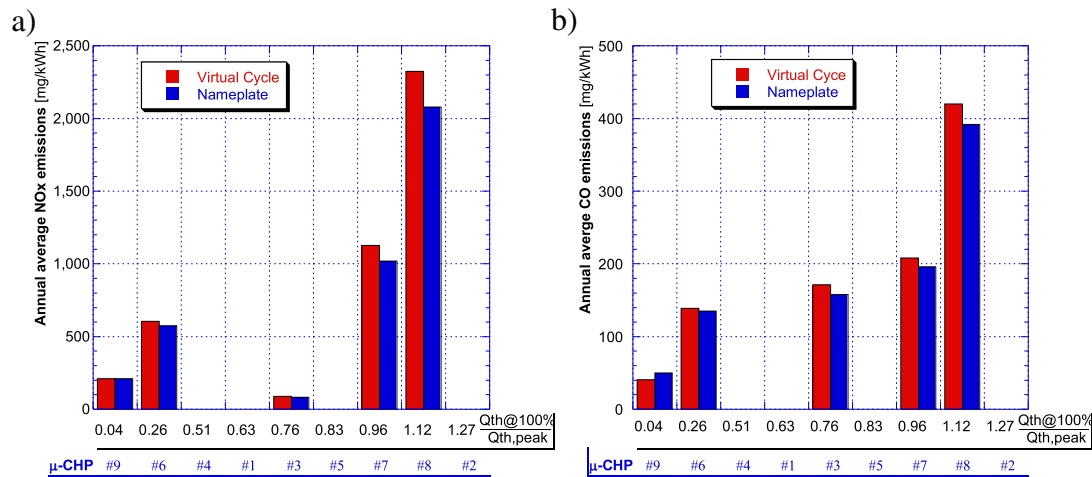


Fig. 13. Estimated average and nameplate emission factors a) NOx emissions; b) CO emissions.

5. Conclusions

The methodology described in this paper allows to roughly estimate in advance the actual energy/environmental performance of a CHP system, starting from limited information on the prime mover nominal performance, i.e., efficiency at various output load operating conditions. Thus, a virtual operating cycle of a μ -CHP system, described in terms of operating hours at corresponding output load and efficiency/emission factors values, can be introduced. Numerical results are presented concerning different μ -CHP systems operated within a modeled demand scenario characteristic of a domestic user. The paper results show a good agreement between the CHP annual performance calculated with the introduced simplified approach and a more detailed performance prediction based on the actual monotonic demand curve and μ -CHP part load efficiencies. Differences between the two approaches in terms of calculated annual mean values are lower than 6 percentage points for thermal efficiency and less than 2 percentage points for electric efficiency. Annual emissions calculated with the proposed approach can differ from the nameplate conditions: few provided examples shown that NOx and CO emission estimations can easily be 5–10% higher than the values corresponding to nameplate emission factors.

Nomenclature

Symbols

f	empirical factor [–]
K	empirical coeff. [h^n]
h	hours [h]
n	empirical coeff. [–]
P_{el}	electric power
PES	Primary Energy Saving [–]
$R(t)$	actual demand
$S(t)$	simplified model demand
t	time [h]
Q_{th}	thermal power
δ_p	pollutant specific emission [mg/kWh]
η_{el}	electric efficiency [–]
η_{th}	thermal efficiency [–]

Subscripts

1	first point
2	second point

DES	nominal or design
i	of the i -th load set point
peak	at the peak
S	average over the year, calculated with $S(t)$
TOT	total in one year

Acronyms

CHP	Combined Heat and Power
FC	Fuel Cells
ICE	Internal Combustion Engine
MGT	Micro Gas Turbine
MRC	Micro Rankine Cycle
SE	Stirling Engine
TPV	Thermo Photo Voltaic

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